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MICRO-IRRIGATION: ADVANCES IN SYSTEM DESIGN AND MANAGEMENT

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Economic and agronomic strategies to achieve sustainable irrigation

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Abstract The achievement of sustainable irrigation in arid regions requires greater attention to waterlogging, salinization, and degradation of ground and surface waters, which are among the problems that continue to threaten productivity and degrade environmental quality. We consider sustainability to be achieved when irrigation and drainage are conducted on-farm, and within irrigation districts, in a manner that does not degrade the quality of land, water, and other natural resources, either on-farm or throughout an irrigated region. Sustainability may also be described as maintaining the productive resources required for irrigation, so that future generations may have the same opportunity to use those resources as we do. Given the increasing importance of irrigated land for food production, the time has come when it is vital to intercept, reuse, and isolate drainage waters within the regions in which they are generated. Adoption of this strategy can be enhanced by policies that require farmers, and irrigation districts, to consider the off-farm impacts of irrigation and drainage. Such policies include linking water rights with salt rights to require the monitoring and management of both irrigation water and the salt loads in drainage waters. We review the knowledge gained since the early 1970s regarding the economic and agronomic aspects of irrigation and drainage, with a focus on drainage water reduction and sequential reuse of drainage water on salt-tolerant crops. Economic incentives that motivate farm-level and district-level improvements in water management are also reviewed. We conclude that adequate knowledge exists for implementing strategies that focus on water use and salt disposal within irrigated regions, and we recommend policies that will motivate improvements in productivity and enhance the likelihood of achieving sustainability.

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Introduction

Only about 17% of the world's cropland is irrigated, but that land produces more than one-third of the food and fiber harvested worldwide (Hillel 1991). Expansion of irrigation in the period between the mid-1960s and mid-1980s accounted for more than 50% of the increase in global food production during that time. In India, this figure approaches 100% (El-Ashry and Duda 1999). Expansion of irrigation will need to keep pace with the increasing world population. However, expansion will not be as easy as it was in the past, given the loss of irrigated lands to salinization, and increasing competition for limited supplies of good-quality irrigation water and the rising costs of developing those supplies.

Future water demands can be met, in part, by using available water supplies more efficiently. Increased use of municipal wastewaters and irrigation drainage waters will also become necessary. The salinity (total salt content) and sodicity (sodium content) of these waters will be higher than that of the original source water because of the direct addition of salts to the water and the evapoconcentration that occurs as water is reused. Higher salinities and sodicities impair crop productivity and farm profits, thereby affecting the ability of farmers to remain in business (Letey 1994) and increasing the inevitable negative off-site environmental impacts of irrigated agriculture (National Research Council 1989).

Sustainability issues

Increasing the production of food and fiber to support a larger world population requires that we improve the performance and enhance the sustainability of irrigation systems in many regions. Irrigation performance is described by the value of outputs and amenities generated in comparison with the level of inputs and opportunity costs required to operate and maintain an irrigation system. Performance is evaluated by analyzing water deliveries, crop yields, and the market prices of inputs and outputs (Molden et al. 1998; Droogers et al. 2000). Sustainability describes the likelihood that an irrigation system will continue to generate desirable outputs and amenities at reasonable costs in future. Hence, the analysis of sustainability requires a broader framework than is used to evaluate irrigation performance. Sustainability is achieved when irrigation and drainage are conducted in a manner that does not degrade the quality of land, water, and other natural resources that contribute to agricultural production and environmental quality. This view of sustainability may also be described as maintaining the productive resources required for irrigation, so that future generations may have the same opportunity to use those resources as that afforded to the present generation (Pearce et al. 1994; Pereira et al. 1996; Dubourg 1997; Solow 2000; Quiggin 2001).

We believe that sustainable irrigation can be achieved if issues regarding efficient irrigation, drainage management, and salt disposal are addressed directly by farmers and public officials. The wealth of knowledge regarding the physical aspects of irrigation and drainage in arid regions can be combined with experience regarding economic incentives to design policies that will motivate farmers and irrigation districts to seek long-term, sustainable solutions to the age-old problems of waterlogging and salinization (Hillel 1991). The solutions should involve farm-level and regional efforts to intercept, isolate, and dispose of saline drainage water (Rhoades 1989), rather than allowing excess water and salts to reduce productivity on lower lying irrigated lands or to degrade the quality of rivers and groundwaters. Intraregional salt disposal on the land surface will require careful management, including mitigation, to minimize agricultural and environmental impacts (Letey 2000). Environmental regulations and economic incentives will enhance the rate at which these strategies (intercepting, isolating, and disposing of drainage waters) are implemented. The benefits for users of groundwater and surface waters—down-slope, down-canal, and down-river—will include greater agricultural production, improved water quality for municipalities, and enhanced amenity values (i.e. boating, swimming, bird watching, sightseeing, etc.].

Professor A.K. Biswas (1997) describes three factors to consider when evaluating policies to promote sustainable water development: (1) short-term versus long-term perspectives; (2) externalities; and (3) risk and uncertainty. The time dimension pertains to the short planning horizons of most farmers compared with what might be considered socially optimal. The latter may include several generations, while the former may be as short as one season. Although a short-term horizon can maximize farm-level profits, farm-level decisions are often not socially optimal because long-term impacts such as waterlogging and salinization are not considered sufficiently in the absence of policies that encourage farmers to take a longer view.

Regarding externalities, Professor Biswas notes that taxes, subsidies, and regulations are standard policy recommendations, but suggests that their implementation is quite challenging in practice, even in developed countries. He notes that precise values of externalities are difficult to calculate; in part, because some externalities develop over long periods of time. In addition, powerful individuals and organizations can influence the policy process. Although it is easier to describe externality policy in concept than to design and implement successful policies, there is no alternative to continuing the search for viable policy tools. Sustainability of large-scale irrigation systems requires that farmers and irrigation districts consider the impacts of their activities on neighboring farmers and districts, to maximize the sum of net benefits generated with limited resources.

Risk and uncertainty are inherent in complex natural systems, such as irrigation, in arid regions where waterlogging and salinization perpetually threaten productivity and sustainability. In nations with rapidly expanding populations and limited economic resources, risk and uncertainty should be addressed explicitly when evaluating policy alternatives for motivating the efficient use of land and water resources. For example, the sustainability of an arid-zone irrigation project may be enhanced if efforts to collect and dispose of saline drainage water are implemented early in the life of the project, given the high probability that an aggressive salt management program will always be required to maintain productivity.

Professor Biswas concludes his discussion as follows: "If sustainable water development is to become a reality, national and international organizations will have to address many real and complex questions, which they have not done so far in any measurable and meaningful fashion. If not, and unless the current rhetoric can be translated into operational reality, sustainable development will remain a trendy catchphrase for another few years, and then gradually fade away...."

We agree with the perspective that serious efforts should be made to motivate the efficient use of land and water resources, particularly in arid regions where waterlogging and salinization and increasing water demands are serious issues. The off-farm impacts of irrigation and drainage involve all three factors described by Professor Biswas, and policies designed to reduce off-farm impacts should address those factors explicitly. Waterlogging and salinization are classic examples of externalities that arise when farmers, or their irrigation districts, are not required to consider the off-farm or downstream impacts of excessive irrigation or the salt loads in surface runoff and deep percolation. Policies that assign responsibility to farmers and irrigation districts for both the source water and salt loads in surface and subsurface return flows from irrigation would likely reduce the areal extent of waterlogging and salinization in arid regions. The probability of success is enhanced when such policies are implemented by a local or regional agency that works with farmers when designing policy measures and selecting parameter values. Examples include the Catchment Management Authorities that address waterlogging and salinization problems in Australia (Anon. 1999; Quiggin 2001) and the Grassland Area Drainage Authority formed to reduce the discharge of agricultural drainage water into California's San Joaquin River (Quinn et al. 1998).

Long-term and off-site effects of irrigation and drainage

The long-term effects of irrigation in arid regions have been known for millennia (Jacobsen and Adams 1958). They still occur in many regions of the world. In his book, *Out of the Earth*, Daniel Hillel (1991) summarized the situation at that time as follows: "It is a disconcerting fact that irrigation farming in very many areas falls far short of achieving its potential. Is the problem intrinsic to the principle of irrigation as such, or merely to the careless practice of it? Must irrigation necessarily become self-destructive sooner or later, or can it be sustained in the long run? Experience leads me to believe that the problem lies in mismanagement. What is at fault is the unmeasured and generally excessive application of water to the land, with little regard either for the real cost of the water—in contrast with its arbitrarily set price, which frequently is too low—or for the potentially destructive processes thereby set in motion. Another frequently and closely related fault is the failure to provide for drainage and to manage the salts as well as the water so as to prevent the insidious process of soil salinization." As pointed out by Wilford R. Gardner in his review of Hillel's book: "Just because we know our history does not mean that we are not doomed to repeat it."

According to E.W. Hilgard (1889), "It is hardly necessary to go further into the details [of the problems occurring in India] to enforce the lesson and warning they convey to our irrigating communities. The evils now besetting [California's irrigation districts] are already becoming painfully apparent; and to expect them not to increase unless the proper remedies are applied is to hope that natural laws will be waived in favor of California. The natural conditions under which the irrigation canals of India have brought about the scourge, are exactly reproduced in the great valley of California; and what has happened in India will assuredly happen there also."

Before about 1970, the main concern on the part of agronomists and engineers was limited to salinity effects on crop productivity, its control within the root zone by leaching, and drainage water disposal. Since then new concerns have arisen (van Schilfgaarde 1994), namely off-site effects of irrigation including (1) increased salinity levels in the drainage water, making it is less suitable for irrigation and for industries and municipalities; and (2) minor elements, such as selenium, in drainage water, which can be toxic to fish and birds (National Research Council 1989). Add concerns about high nitrate levels, and low but potentially dangerous levels of various pesticides, and it is clear that managing soil salinity and drainage waters has become substantially more difficult and controversial. Hence, the time has come to seriously consider the interception, isolation, and reuse of drainage waters—or more to the point, the salts they contain—within the regions in which they are generated (Rhoades 1989).

For irrigated areas within hydrologically closed inland basins, the final disposal site for drainage water, and particularly the salt it contains, could be evaporation ponds or, less desirably, underground strata. However, salt disposal on low-lying lands through indiscriminate waterlogging should be discouraged. Instead, the dedication of those lands for cyclic and sequential reuse of saline-sodic drainage waters should be encouraged. Sequential reuse will reduce the volume of drainage water needing disposal, thus enhancing the economics of disposal in evaporation ponds and underground strata, export to the nearest ocean, or treatment to remove toxic constituents. These same strategies can be used in irrigated areas where drainage water flows into river systems that discharge into oceans. Less water would be diverted in the first place and salt loads in return flows would be reduced, as would interregional concerns about river water quality (Rhoades 1989).

The role of economic incentives

Economists often describe the externalities and opportunity costs associated with irrigation and drainage that prevent a region from maximizing the net benefits generated with limited land and water resources. Externalities, the off-farm effects of irrigation, involve costs or benefits imposed on other farmers or the public. Positive externalities involve benefits, such as the generation of usable surface runoff or the provision of water supply to a desirable wetland area. Negative externalities involve short- and long-term damage caused by surface runoff, deep percolation, and saline drainage water. Examples include groundwater degradation (Quinn 1991), waterlogging and salinization in the tail-end areas of tertiary canals (Bromley et al. 1980; Skold et al. 1984; Bhutta and Vander Velde 1992), and the off-farm impacts of saline drainage water that degrades the quality of rivers in an irrigated region (National Research Council 1989).

Several of these externalities are caused by excessive irrigation that occurs when property rights to water and drainage discharge are not defined, or not enforced, or when water prices are too low to motivate farm-level expenditures to improve water management. Farmers may also lack sufficient knowledge of crop water requirements, alternative irrigation methods, and the impacts of their irrigation and drainage activities on neighboring farms and districts.

Opportunity costs are the incremental values of water in alternative uses, such as the value that might be generated by irrigation on a downstream farm or by the use of water in a non-agricultural activity. For example, a head-end farmer diverting water from a tertiary canal on which the water supply is limited to a 7-day rotation imposes an opportunity cost on tail-end farmers who are unable to obtain canal water. Farmers pumping groundwater from an aquifer that receives negligible recharge impose an opportunity cost on future generations with each cubic meter they remove from the aquifer.

The environmental degradation and inefficiencies that arise due to externalities and opportunity costs can prevent a region or nation from achieving sustainable irrigation. For example, waterlogging, salinization, and groundwater overdraft will eventually reduce the productivity of irrigated agriculture. Efforts to achieve sustainability must include policies that motivate farmers to reduce negative externalities and consider opportunity costs when choosing irrigation and drainage strategies. Economic incentives can provide that motivation.

Policies that promote intercepting and isolating drainage water, and disposing of associated salts, include economic incentives to reduce excessive water deliveries, such as increasing block-rate pricing of irrigation water in which the per-unit price of water rises with the volume delivered to a farm or field. Price structures can also be designed to encourage farmers to choose irrigation methods and management strategies that minimize subsurface drainage and deep percolation. Other policies include a "salt surcharge" that reflects the cost of salt disposal. Salt loads in drainage water depend both on the salt load in irrigation water and the native salts present in most arid-zone soils. Adjustments could be made to account for dissolution of native salts contained in the soil as a consequence of irrigation. The resulting price system would be similar to an increasing block-rate pricing structure, and would provide an added emphasis on salt loads generated by irrigation and the need to manage them in a sustainable manner throughout an irrigated area. In a sense, farmers would be paying a "deposit" on salt loads generated by irrigation. The revenue collected could be used to intercept, isolate, and dispose of those salts.

Increasing block-rate prices and salt load surcharges would motivate farmers to improve water management practices and reduce excessive deep percolation in ways that will enhance regional salt management efforts. Water pricing policies obviate the need to measure accurately the volume of deep percolation or the salt loads generated by irrigation. Only an accurate estimate of the per-unit cost of collecting and disposing of salt, either within or outside the region, is required to determine the appropriate water prices. The salt surcharge would motivate farmers to choose irrigation methods that will reduce regional salt loads. This concept can be extended to regional levels by allowing irrigation and drainage districts to buy and sell emission permits for drainage water, or for the loads of salt and other elements in drainage water. Examples of such programs include the trading of selenium loads among irrigation and drainage districts in California's San Joaquin Valley and the inter-state market in salt emission permits in Australia's Murray-Darling River basin (Brennan and Scoccimarro 1999).

One goal of these economic incentives is to assign the same level of responsibility to farmers and irrigation districts regarding salt management as is typically assigned regarding water supply and irrigation management. None of these policies can be implemented without cost and we recognize the difficulty of implementing innovative policies in areas where institutions and infrastructure are not yet fully developed. However, we believe it is helpful to describe policies that will promote sustainability, so that regional and national agencies may begin making the enhancements in institutions and infrastructure needed to support them. One such enhancement is the formation of regional irrigation and drainage agencies.

A regional policy perspective

Regional agencies may be required to implement appropriate pricing structures and coordinate activities required to manage regional salt loads efficiently. Local irrigation districts are often formed for the purpose of obtaining and delivering water supplies, without regard for impacts on regional salt loads. Similarly, local drainage districts are formed for the purpose of collecting and disposing of surface runoff and saline drainage water to relieve localized high water tables. Local districts are often unable to reduce the contribution to those water tables from farms outside the district.

The goals of a regional irrigation and drainage agency might include enhancing agricultural productivity, managing salt loads, and achieving regional water quality objectives at minimum cost. Given its regional perspective, such an agency could maximize the value of any economies of scale in designing and implementing technical measures to intercept, isolate, and dispose of saline drainage water. For example, a regional agency could support farm-level improvements in water management, installation and modification of subsurface drainage systems, water-table management, recycling of drainage water, irrigation with drainage water on specific crops and lands, and drainage water treatment.

A regional agency could generate revenue with a fixed-rate land assessment and a variable charge on water deliveries that reflects the per-ton cost of disposing of salt. The agency could compensate farmers and districts that agree to recycle drainage water or to make land available for sequential irrigation with waters of increasing salinity. Such programs would, in a sense, use funds collected from all farmers generating excessive salt loads to compensate farmers willing to incur additional expenses to support regional salt management efforts. The likelihood of designing and implementing innovative policy measures can be enhanced by regional data collection and extension efforts that improve the understanding of irrigation and drainage relationships, water-use efficiency, and farm-level water management strategies.

Programs implemented by a regional agency could be enhanced in future, as experience is gained regarding the impact of incentives to encourage improvements in farm-level water management, and with regional efforts to intercept, isolate, and dispose of salt. For example, an agency might implement quantitative restrictions on salt loads applied to farmland or on the net salt loads moving into the vadose zone. Programs may also change with improvements in technology that enable more accurate measurement of salt loads moving between farms. In addition, a regional authority might implement long-term projects, such as the construction of drains or pipelines for conveying saline drainage water or brine to appropriate salt sinks, in a manner that reduces the cost of achieving regional water quality objectives.

Knowledge advances since 1970

Salt loads of drainage water

Before 1970, the concept of salt balance was thought to be the key to irrigation sustainability. Salt loads in drainage waters needed to equal the salt applied in the irrigation water. However, salt load depends on the percentage of the water diverted that is used by the crop. Salt load can be reduced by precise irrigation that limits the leaching fraction to the amount needed to maintain crop yields at acceptable levels. At high leaching fractions, water that passes through the root zone tends to dissolve salts; at lower leaching fractions, precipitation of calcite and gypsum can occur (Rhoades et al. 1974). These changes in salt loading are predictable based on the inorganic chemistry of mixed salt solutions (Oster and Rhoades 1975).

In many areas, drainage water does not flow directly back to the rivers from which the irrigation water was diverted. Saline geologic deposits often exist along the flow path. Passage of return flows through these deposits can result in large increases in the salt loads of these return flows. This occurs in the Grand Valley of Colorado where the saline Mancos shale underlies irrigated lands. Reducing the return flows by lining canals and increasing the fraction of the irrigation water used by the crop will improve water quality in the river by reducing both the amount of water diverted and the salt load returned to the river. The costs of those efforts may be attributed, in part, to the inherent difficulty in developing sustainable irrigation in a region where saline geologic deposits generate undesirable off-site impacts. That situation pertains also to the west side of California's San Joaquin Valley, where selenium that occurs naturally in the region's soils moves into regional drainage ditches and enters the San Joaquin River, causing concerns among biologists and water quality authorities regarding potential impacts on aquatic wildlife. In both the Grand Valley and the San Joaquin Valley, early irrigators likely were not aware that natural geological conditions would someday complicate efforts to achieve sustainable irrigation.

Irrigation uniformity

The uniformity of water application and infiltration, and the targeted crop yield, have a major impact on drainage water volume (Letey 1993). For example, the volume of drainage water generated in the course of applying sufficient water to obtain 100% and 90% of maximum yields for cotton (*Gossypium hirsutum* L.; salt-tolerant) and corn (*Zea mays* L.; salt-sensitive) rises as irrigation uniformity declines (Table 1). Irrigation uniformity is characterized by standard deviation (SD), which increases with decreasing uniformity.

To maintain yield as the salinity of irrigation water (EC_i) increases, more water must be applied and more drainage water produced. The increase is greater for the salt-sensitive corn than salt-tolerant cotton. The value is also strongly dependent on desired yield. Drainage is considerably higher for target yields of 100% than for 90% (Table 1). Clearly, precise irrigation management to apply water uniformly limits the drainage water and leaching fraction to levels needed to maintain full crop growth, substantially reducing both drainage water volume and salt load.

Microirrigation (drip and microsprinkler)

Precise irrigation is possible with microirrigation methods, which deliver water from piped mainlines and laterals to the root zone frequently in small amounts, and at rates matched to crop needs. Microirrigation techniques are the best method to use with saline water (Shalhevet 1994). Costly systems? Yes. However, as Hillel (1991) points out, "It is often said that such modern methods are too costly for adoption in less developed countries, so these countries have no choice but to remain with their traditional methods of surface irrigation, conveying water in open channels and running over the surface of the ground—this ignores the

Table 1 Impacts of irrigation water salinity (ECi) on the amount of drainage water (cm) necessary to achieve 100 or 90% yield of cotton or corn when irrigated at various levels of uniformity (SD). Calculated from applied water given in Letey (1994, Table 4-1) by subtracting the crop ET as specified below

ECi, dS/m	Target yield of 100%			Target yield of 90%		
	SD			SD		
	0.01	0.27	0.4	0.01	0.27	0.4
	Cotton (ET of 72 and 56 cm at 100% and 90% yield, respectively)					
0.1	1	33	> 48	1	8	17
2.0	5	38	> 48	5	12	22
4.0	18	> 48	> 48	10	19	29
8.0	–[a]	–[a]	–[a]	26	39	49
11.0	–[a]	–[a]	–[a]	54	64	> 64
	Corn (ET of 67 and 60 cm at 100% and 90% yield, respectively)					
0.1	1	43	> 53	1	9	18
1.0	16	> 53	> 53	9	18	29
4.0	–[a]	–[a]	–[a]	–[a]	–[a]	–[a]

[a] Target yield cannot be achieved regardless of the amount of applied water.

hidden costs of water wastage and of land degradation, as well as the increased environmental costs of drainage and land reclamation. If they are taken into account the relative costs of modern versus traditional irrigation methods will change radically.''

Investment costs for pressurized systems are considerably higher than for gravity-flow systems. From the farmer's economic viewpoint, improvements in productivity must be sufficient to justify investing in higher cost systems. An economic analysis of irrigation systems for cotton production in California (Letey et al. 1990) indicates that gravity-flow systems are more profitable than pressurized systems when no costs or restrictions are imposed on drainage water disposal. However, the farm-level economics of pressurized systems improve when farmers are faced with drainage water fees or disposal constraints.

Several field experiments conducted in California since about 1985 support the position that dripirrigation on some row crops is potentially more profitable than surface irrigation. In a large-scale (16 ha per treatment) field experiment, at Harris Farms on the west side of the San Joaquin Valley, a subsurface drip system generated greater profits than improved or historic furrow systems, due largely to an increase in average cotton yields. Costs of the three systems were $677/ha for the subsurface drip system, $301/ha for the improved furrow system, and $166/ha for the historic furrow system (Styles et al. 1998). The average annual net income per hectare was $660 for subsurface drip, $504 for improved furrow irrigation, and $588 for historic furrow irrigation. In another field comparison of subsurface drip to furrow irrigation, conducted about 50 km distant from Harris Farms on a more productive soil with historically higher cotton yields, subsurface drip was somewhat less profitable than furrow irrigation (Smith and Oster 1991). A possible explanation for this different response is that when all other productivity factors are equal, improving irrigation uniformity results in larger yield gains on nonuniform soils than on uniform soils.

Microirrigation cannot be justified economically on all crops at prevailing input and output prices, but the relative cost of microirrigation will decline when water prices or allotments are adjusted to reflect the off-farm and long-term impacts of irrigation and drainage activities. For example, microirrigation will gain attractiveness if farmers are made responsible for the disposal or reuse of surface runoff and subsurface drain water. A tax on groundwater withdrawals in a region where demand exceeds the natural rate of recharge will have a similar impact on the relative cost of microirrigation. In addition, widespread adoption of policies that require or motivate farmers to reduce off-farm impacts may encourage entrepreneurs to develop lower-cost microirrigation systems that are financially feasible on a wider range of crops and in a broader set of production environments (Polak et al. 1997; Postel et al. 2001). It also may be appropriate for governments and donor agencies to subsidize investments in microirrigation development and adoption in regions where the social benefits of ending the unsustainable overdraft of limited groundwater resources would be substantial.

Drainage water reuse for crop production

The capture and reuse of saline and saline-sodic drainage water, which is feasible based on farmer and research experience, could play a key role in reducing its volume. Farmers in many nations have successfully used waters that are conventionally classified as moderate to severely saline to irrigate a broad spectrum of crops (Ayers and Westcot 1985; Rhoades et al. 1992). The methods include cyclic and sequential reuse, and blending. Although blending drainage water with good quality irrigation water is widely practiced in India

(Minhas 1996) and California (Wichelns et al. 1988), there can be significant and undesirable impacts due to degraded water quality on downstream users. Cyclic and sequential reuse strategies, although less simple to manage than blending, provide the means of isolating salinity impacts to a more local, smaller scale and to take advantage of an increasing salt tolerance of plants as they mature (Pasternak et al. 1986; Maas and Poss 1989). Rhoades (1999) argues, with considerable justification, that "more crop production can usually be achieved from the total water supply by keeping the water components separated."

Sequential reuse

This option involves applying the best-quality water to the crop with the lowest salt tolerance, then using the drainage water from that field—obtained from tile drainage systems—to irrigate crops, such as Bermuda grass (*Cynodon dactylon*), that are more salt tolerant. The simplest management method is to use drainage water sequentially on fields located downslope from those where the drainage water is collected.

In California, sequential reuse experiments have involved the use of trees, particularly Eucalyptus (Cervinka 1994) as the first crop irrigated with drainage water and the halophyte *Salicornia* as the second and final crop. *Salicornia* trials have demonstrated that it uses highly saline water efficiently (Grattan et al. 1999), but the yields of its oil-bearing seeds have been low. The fact that vegetable oils are already abundant and not easily marketed complicates this situation. Further, Eucalyptus trees have either grown poorly or, where growth has been good (due to the use of gypsum to maintain good soil physical conditions), water use was reduced because the salinities in the root zone exceeded the threshold salinity. In addition, local firewood markets are unlikely to be profitable (Oster et al. 1999a).

In the San Joaquin Valley of California, forage cropping systems based on sequential reuse of saline-sodic drainage water hold promise (Oster et al. 1999b). Preliminary field tests have demonstrated that Bermuda grass can be grown using water as saline as 17 dS/m with SAR levels exceeding 25.

Cyclic reuse

In this strategy, the availability of good-quality irrigation water or a soil with low salinity, particularly before and during the early stages of plant development, facilitates the use of moderately saline irrigation waters later in the growing season. Less tolerant crops might require cyclic (re)use of good quality water to establish the crop and drainage water reuse for part of or all of the remainder of the growing season. Moderately tolerant and salt-tolerant crops can be irrigated with saline water with little yield loss after they have reached a salt-tolerant stage of growth. After the salt-tolerant crop is grown, a pre-irrigation with low salinity water reclaims the upper portion of the soil profile in order to establish the salt-sensitive crop.

Field studies on the cyclic reuse of saline-sodic (EC: 4–8 dS/m; SAR: 10–33) drainage water for irrigation conducted in California since about 1975 (Grattan and Rhoades 1990; Drainage Reuse Technical Committee 1999) have demonstrated that this strategy is sustainable on a broad range of soils, provided that correct use is made of gypsum to control problems with crusting and poor aeration. The latter is a problem particularly during a rainy season (Oster and Jayawardane 1998).

Water-table management

Reuse should be coupled with water-table management to maximize drainage water reduction. Shallow groundwater contributions to crop water use by cotton and alfalfa ranged from 19 to 60%, depending on the water-table depth and its salinity (Ayars 1996). Groundwater contributions usually are largest when the roots are fully developed after which the crop is deliberately underirrigated. Bradford and Letey (1992) simulated the effects of a high water table and irrigation scheduling on cotton production and found that higher yields were achieved by applying less water during the crop season and more during the pre-irrigation for salt leaching purposes. Their results also indicated that where the water table was saline and no drainage occurred over a period of several years, high cotton yields could be sustained if the irrigation water was low in salinity. Salt accumulation occurs slowly in the lower portion of the root zone using this method and could be controlled by infrequent leaching. In addition to underirrigation of the crop during its mature stages, new design criteria for subsurface drains are needed. The targeted depth to the water table midway between drains needs to be reduced from about 1.2 m to 1.0 m or less. The placement of the laterals needs to be more or less perpendicular to the slope, valves should be placed on the laterals, and depth control structures installed along the submains and at the outlet.

Computer models: aids for design and management

Model predictions provide a glimpse into the future. Some of the computer models available today provide deterministic or mechanistic looks at: (1) transient water and salt movement and inorganic chemistry as affected by irrigation water and crop management (Suarez and Simunek 1997); (2) the effects of salinity on both crop yields and water use (Letey et al. 1985; Cardon and Letey 1992); and (3) drainage system performance related to drain spacing and depth (Skaggs 1999). The drainage data in Table 1 provide an example of how the production function model can be used to project impacts of irrigation uniformity, salinity, and yield target on both irrigation water requirement and drainage. Similar models will be used in the future to design, plan, and manage irrigation systems that use two or more sources of water with different salinities, and to design drainage systems that facilitate crop use from shallow, saline water tables. Transient salinity models will provide insights into the long-term temporal changes in salinity and sodicity, enabling researchers and engineers to assess possible changes in the soil's ability to conduct water and gas, changes that will likely take many years to occur.

Economic incentives

Economists have learned a great deal since 1970 regarding the role of economic incentives in motivating the efficient use of irrigation water and protecting the environment. Incentives enhance the likelihood and reduce the cost of achieving policy goals, when compared with moral suasion and regulation (Knapp et al. 1986; Gardner and Young 1988; Dinar et al. 1989). In practice, economic incentives are often implemented after initial attempts to reduce effluent using moral suasion fall short, or when the high costs of implementing and complying with regulatory standards become evident.

Economic incentives are useful particularly when addressing nonpoint source pollution and when regulatory agencies have limited information regarding the technical and economic parameters that affect farm-level decisions (Griffin and Bromley 1982; Shortle and Dunn 1986). Incentives can be designed to motivate short-term reductions in effluent and long-term investments that will reduce the volume of effluent generated per unit of agricultural production (Knapp 1992a, 1992b, 1992c; Dinar et al. 1993). Incentives also may be used in combination with regulatory standards when more than one policy tool is needed to achieve a given objective. For example, higher farm-level prices for irrigation water can be implemented in conjunction with district-level discharge limits to reduce regional drainage water volume.

Policies that incorporate economic incentives can be classified as those that involve inputs in agricultural production and those that involve effluents, such as salt, silt, nutrients, and other constituents in surface runoff and deep percolation. Optimal input policies based on the underlying causes of externalities encourage farmers to consider the external costs of their decisions regarding production activities and irrigation inputs. For example, negative externalities along tertiary canals occur largely because property rights to water are not assigned or not enforced, and often there is no charge for water deliveries. Economic incentives can be helpful in motivating head-end farmers to account for the impacts of their activities on middle-reach and tail-end farmers.

It is more difficult to implement incentives that address effluent directly in cases of nonpoint source pollution, because the cost of identifying and measuring the volume or load of effluent generated by individual farmers is prohibitive. Incentives that address input choices are more appropriate in cases of nonpoint source pollution. However, the effectiveness of those measures will vary with the degree to which relationships involving inputs and effluent are understood and incorporated into the incentive mechanisms. For example, a surcharge imposed on water deliveries to motivate a reduction in drainage water volume must be greater than the incremental cost of improving farm-level water management, or the surcharge will generate additional revenue to the water supplier without accomplishing the policy objective.

Policies that seek to modify farm-level input choices have been implemented to address several nonpoint source problems in agriculture. For example, farmers have been encouraged to use "best management practices" to reduce soil erosion and nutrient loads that degrade water quality (Anderson et al. 1990; Izuno et al. 1999). Farmers on the west side of the San Joaquin Valley were asked to implement best management practices when selenium problems were observed at the Kesterson National Wildlife Refuge in the mid-1980s (Letey et al. 1986).

Several empirical studies describe the role of economic incentives in motivating improvements in water management to reduce drainage water volume and constituent loads in the San Joaquin Valley. Dinar et al. (1993) show that quotas and taxes on surface water deliveries motivate greater reductions in aggregate water use than restrictions on drainage water volume. Wichelns (1991a) and Wichelns et al. (1996) report reductions in water applications ranging from 9% on tomato fields (from 926 to 847 mm) to 25% on cotton fields (from 1,000 to 749 mm) in the 4,000-ha Broadview Water District as a result of implementing block-rate prices and other economic incentives. Empirical results will vary with location and with farm-level water prices, allotments, the value of crops produced, and the costs of improving water management practices. Broadview farmers were motivated both by district-level economic incentives and by regional efforts to reduce drainage water volume.

Four types of incentives may be implemented to modify the on-farm price or opportunity cost of irrigation and drainage inputs:

1. Water allotments or water rights,
2. Water marketing among farmers, basins, and economic sectors,
3. Higher prices for irrigation water, and
4. Subsidies and fees.

The optimal combinations of these incentives vary with the ability to control and measure water deliveries, and the level of development of local institutions, such as irrigation and drainage districts.

Water allotments

Farm-level water allotments encourage farmers to consider crop water requirements carefully when choosing crops and irrigation methods. Hence, allotments are particularly helpful in regions where the available water supply is insufficient to meet crop water needs or the distribution of water among farmers is uneven. In Mexico, the National Water Commission has transferred responsibility for the operation and maintenance of secondary and tertiary canals to water user associations that allocate water according to each farmer's proportion of the total irrigable area (Kloezen and Garces-Restrepo 1998; Levine et al. 1998). Some associations use farm-level crop intentions to determine water allocations, effectively restricting the area planted to crops with large water requirements during dry years. Others allocate each year's water supply among farmers, allowing them to choose their crops accordingly.

Allowing farmers to trade their allotments individually, or as members of water user associations, can reduce negative externalities and encourage greater consideration of opportunity costs. The national groundwater agency in the Cape Verde Islands has implemented a fixed-access rotation system, replacing one in which farmers could withdraw as much water as desired during each rotation. The new system reduces both uncertainty regarding water allotments and the time interval between rotations. Farmers trade access times to gain the flexibility required for producing higher valued crops (Langworthy and Finan 1996).

Water markets

Policies that allow farmers to sell or lease water to other farmers and to non-agricultural water users complement farm-level allotments by enhancing the value of the opportunity cost of water. The prices that buyers are willing to pay for water motivate farmers to improve irrigation practices in ways that reduce surface runoff and deep percolation, such as hiring additional irrigators and replacing surface irrigation methods with sprinklers and micro-irrigation systems. Subsequent reductions in water deliveries and drainage water volume may reduce negative externalities in areas such as California's San Joaquin Valley, where selenium-rich drainage water flows into the San Joaquin River (Dinar and Letey 1991; Letey et al. 1986). Weinberg and Willey (1991) suggest that drain water volume can be reduced by 30% in that region (from initial average depths ranging from 275 to 380 mm) if farmers are able to market a portion of their water supply at prices ranging from \$65 to \$105/ML. Those prices, which are higher than agricultural water costs in most years, are within the range of prices paid by municipal water companies. The 30% reduction in drain water volume would be sufficient to achieve the selenium water quality objectives established by the California Regional Water Quality Control Board (California SWRCB 1987), and likely could be achieved by improving water management practices while maintaining or improving crop yields.

Tradable water rights were introduced in South Australia in 1983 to enhance water-use efficiency along the Murray River. Water marketing has led to an increase in the production of higher valued crops using more efficient irrigation methods, while the volume of water applied to lower valued crops has declined (Bjornlund and McKay 1998). Water markets have also enhanced the benefits generated with limited water supplies in Pakistan, northern India, and Chile (Easter and Hearne 1995; Gazmuri and Rosegrant 1996; Bauer 1997). Complementary policies can be implemented to reduce the likelihood that waterlogging and salinity problems will arise in regions receiving transferred water. For example, farmers purchasing water in South Australia must provide irrigation and drainage management plans, in an effort to limit the impact of return flows from upstream areas on river salinity downstream (Bjornlund and McKay 1998). Salinity zones are defined in the Murray-Darling Basin and the proposed transfer of water from low salinity zones to high salinity zones may be rejected by regional authorities (Brennan and Scoccimarro 1999; Chatterton and Chatterton 2001).

Viable water markets often require institutional enhancements (Colby 1991). Property rights must be clearly defined and the rules that govern water marketing must be clear. Policies that limit the volume of water sold by individuals or districts may be needed to protect the water supply provided historically to downstream farmers. Transaction costs can slow the development of water markets, but public agencies can reduce those costs by providing water market information to potential buyers and sellers, and reducing regulatory requirements regarding water transfers. The gains in water-use efficiency made possible by water marketing may justify the role of public agencies in encouraging water market transactions. Where appropriate, a proportion of the revenue received from water sales and leasing can be retained by a public agency to pay for improvements in irrigation and drainage systems that enhance water productivity and minimize losses to saline sinks.

Water prices

Increasing the unit price of water is appropriate when the policy goal is to communicate an increase in the scarcity value of water in regions with increasing competition for limited water supplies. Higher water prices encourage farmers to reevaluate crop choices and the relative amounts of water, labor, and capital (irrigation and drainage technology) used in crop production. Dinar and Subramanian (1997) and Tsur and Dinar (1997) provide many examples of water pricing programs in various countries.

An increasing block-rate pricing structure is appropriate when reductions in surface runoff or deep percolation are desired. Farmers can avoid higher unit prices for irrigation water by implementing desirable improvements in water management practices that enable successful crop production within lower-priced blocks (Wichelns 1991a, 1991b; Wichelns and Cone 1992; Wichelns et al. 1996). Crop-specific and field-specific forms of block-rate prices are more effective in motivating reductions in surface runoff and deep percolation, but greater efforts are required for water monitoring and program administration (Wichelns 1991b).

Water prices can also provide an economic incentive for public agencies to reduce seepage along main and secondary canals, particularly if agency budgets are made dependent upon the collection of revenue from water sales (Moore 1989; Small and Carruthers 1991; Ellis 1992). Water agency personnel in regions where water is delivered at no charge to farmers and water rights are not assigned have little incentive to spend limited funds on canal improvement projects (Repetto 1986).

Subsidies and fees

Many large-scale irrigation and drainage systems have been constructed using public funds and grants from international agencies because the benefits extend beyond the net revenue earned by individual farmers. Such benefits include expansion of employment opportunities, improvements in rural incomes, and enhanced food security. In a similar fashion, the public may gain by subsidizing improvements in irrigation and drainage practices that enhance sustainability and reduce the concentrations or loads of undesirable constituents in agricultural drainage water.

Public subsidies of large-scale irrigation projects and price supports for selected commodities have enabled farmers in many areas to produce crops that have low market values, although the true cost of land and water inputs may be substantial. Appropriate changes in price support policies and the farm-level cost of irrigation and drainage services may encourage farmers to produce higher valued crops and to improve their management of land and water resources. Policies also may be designed to encourage farm-level adoption of selected irrigation methods, or to discourage the use of undesirable methods. For example, farmers who reduce applied water using sprinklers or micro-irrigation systems might be charged a lower price per unit of water than farmers using furrows or gated pipe. Such a policy places an implicit surcharge on water for farmers using systems that generate larger volumes of surface runoff and deep percolation. However, such a program should allow for the possibility that some farmers using surface methods may generate less drainage water than farmers using micro-irrigation systems. In the final analysis, the level of management invested in irrigation and drainage activities can have a greater impact on drainage water volume than the choice of irrigation system.

Cost-sharing programs and low-interest loans that support farm-level investments in new irrigation equipment provide similar motivation for change. Such programs might be funded by state or local governments that have an interest in seeking improvements in water management that will reduce the volume of drainage water and the loads of salt and other constituents flowing to wetlands and rivers. Irrigation and drainage districts can also implement financial incentive programs with funds collected using block-rate pricing structures.

Financial incentives can also be used to encourage farm-level and district-level improvements in drainage water facilities and management. For example, cost-sharing and low-interest loans can be used to support changes in existing drainage systems that enable farmers to utilize high water tables more effectively in providing a proportion of crop water requirements (Ayars 1996). Incentives might also be provided for installing tailwater ponds, pipelines, and pump stations that enhance farm-level and district-level efforts to collect and recirculate surface runoff and subsurface drain water.

Summary

We believe that the goals of achieving irrigation sustainability and increasing food production are compatible. Research results and the experience gained by farmers and administrators in recent decades are sufficient to support the development of irrigation strategies that focus on both water use and salt disposal, within irrigated regions and subregions. The agronomics of salt management in irrigated agriculture have advanced significantly in recent decades. Agronomists, soil scientists, engineers, and others have moved beyond the concept of maintaining a salt balance that might never be achieved, to describing how salt loads of drainage flows can be managed by changing the leaching fraction. We have developed a better understanding of the role of irrigation uniformity in determining leaching requirements and in generating profitable yields. And we have learned how to manage shallow water tables to obtain a proportion of crop water requirements from water that might otherwise require collection and disposal. The possibilities of further reducing the volume of drainage water by reusing it for crop production are also better understood. For example, when the costs of drainage disposal are significant, micro-irrigation systems become more profitable than surface irrigation systems because of the ability to apply water precisely, thereby reducing the volume of drainage water needed for leaching.

Economists also have made great progress in recent decades in designing and implementing policies that motivate the wiser use of natural resources. They have shown that assigning water rights and allowing farmers to trade those rights can enhance the total value generated with a limited water supply. They have also shown that increasing block-rate prices can motivate farm-level improvements in water management that reduce deep percolation and drainage water volume. Around the world, farmers are responding to various forms of economic incentives, including water pricing, subsidies for investments in irrigation equipment, and fees for drainage services.

In addition, many farmers are paying higher fees for operation and maintenance, and improving delivery services, as national irrigation systems are transferred to water user associations.

In summary, we believe the time has come to combine the impressive gains in the agronomics and economics of irrigated agriculture to reduce waterlogging, salinization, and the salt loading of groundwaters and rivers. In particular, we believe that efforts to intercept, isolate, and dispose of saline drainage water in the region in which it is generated will minimize the off-site and long-term impacts of irrigation and enhance the likelihood that irrigated agriculture can be sustained in arid regions. Successful implementation of this strategy will require complementary efforts that address technical, institutional, and economic aspects of irrigation and drainage at the farm-level and throughout irrigated regions. We have described the following policy measures that may be helpful in supporting those efforts:

1. Support the development of regional irrigation and drainage agencies that can implement technical measures and economic incentives to improve regional and farm-level management of irrigation water and drainage water. Regional agencies can also compile better information describing farm-level water deliveries, crop water requirements, and irrigation strategies to support policy refinements in future.
2. Implement economic incentives that encourage farmers to improve water management practices and reduce excessive surface runoff and deep percolation. Candidate programs include increasing block-rate pricing and salt surcharges on irrigation water applied in excess of crop water requirements.
3. Assign responsibility to farmers for both the irrigation water they divert or purchase from water sources and the salt loads in surface runoff and subsurface drain water.
4. Encourage water marketing among farmers, while providing assurance that transferred water will not generate environmental problems in receiving areas.
5. Promote the development and farm-level adoption of lower cost micro-irrigation systems that are economically viable on a wide variety of crops in many production environments, particularly in arid areas where persistent groundwater overdraft is threatening the sustainability of irrigated agriculture.
6. Conduct further research on cyclic and sequential reuse strategies to maximize opportunities for reducing the volume of saline drainage water requiring disposal or evaporation.

Successful implementation of these policies and strategies is needed to enhance the likelihood that we can achieve sustainable irrigation within a reasonable time horizon and maintain the ability to feed and clothe a rapidly increasing world population.

Concerns regarding implementation

Economic incentives that address externalities are not always accepted immediately by all parties with a direct or indirect interest in maintaining environmental quality or increasing agricultural production. In addition, the strategy of intercepting, isolating, and disposing of salt borne in drainage water may generate some concerns. Proponents of maintaining and improving environment quality would favor reducing the salinity of river systems from which irrigation waters are diverted. They may question salt disposal in evaporation ponds because of potential impacts on wildlife, and they may object to disposal in underground strata. Farmers may resist economic incentives that raise the cost or reduce the supply of irrigation water and they may not support changes that raise the concern for salt management to a level equivalent to that for water allocation and management.

Water resource professionals including engineers, water managers, and economists, may require time to develop a greater focus on salt management, as new techniques, expertise, and specialization will be required to design and support appropriate policies. Economists, in particular, must examine the profitability of existing irrigation systems and characterize potential impacts from changes in policies regarding water allocation, pricing, and regulatory constraints. Scientists usually perceive the situation in terms of unknowns that require more research before changes can be urged upon society in general, and farmers in particular. Finally those with responsibilities, expertise, and abilities to extend information to farmers, districts, and the general public require a fair degree of common agreement about what should be done as a base from which to begin educational programs.

Some of the proposed policies and strategies require technical measurements that may not be feasible at present in many irrigated areas. For example, a salt surcharge on excessive irrigation deliveries requires an accurate estimate of the salt concentration of farm-level soil and water resources; and a successful block-rate pricing program requires accurate measurement of field-level water deliveries. The cost of obtaining such detailed information could not be justified in the past, when water supplies were plentiful and the externalities of irrigation were not extensive. In future, as the scarcity value of irrigation water increases, along with the economic impact of irrigation externalities, public investments in the collection of field-specific soil and water information will become viable in many areas.

Many of the proposed policies can be implemented by regional irrigation and drainage agencies working closely with farmers to design effective programs. In some cases, however, social optimality will require a national or international policy framework. For example, efforts to achieve sustainable irrigation in regions with severe groundwater overdraft may require action by a national government that has broader jurisdiction than a single regional irrigation and drainage agency. International cooperation may be required in areas where threatened aquifers lie beneath international borders, where nations compete for limited surface water supplies, and where drainage water is discharged into rivers that cross regional or international boundaries. Political efforts to implement successful policies in those situations may be substantial, but the potential gains in net social benefits from achieving sustainable irrigation will be equally impressive.

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